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The effect of annealing on magnetostriction of amorphous iron-boron ribbon

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Abstract : The effect of annealing on magnetostriction of the amorphous ribbon having composition $Fe_{82}B_{18}$ in the temperature range 50°C to 300°C has been measured using the conventional strain gauge technique Magnetostriction as a function of field upto saturation value is measured to find the nature of the domain wall movements associated with the magnetization process Saturation magnetostriction is measured by rotating the magnetization from the direction of the measurement of strain to its perpendicular direction It is observed that magnetostriction as a function of field as well as the saturation magnetostriction decreases with increasing annealing temperature. The results are explained as due to the removal of stresses and the associated technical anisotropy which are induced in the ribbon during the process of its preparation by melt spinning technique.

Keywords : Amorphous ribbon, magnetostriction, annealing effect

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In the present paper, the effect of annealing on magnetostriction of iron-boron ribbon, with annealing temperature varied from 50°C to 300°C at intervals of 50°C, is presented. The alloy composition was chosen to be the simplest for avoiding complication in the interpretation of the results. The maximum annealing temperature was kept below the glass transition temperature which for the iron-boron ribbon with composition $Fe_{82}B_{18}$ is determined to be 448°C by differential thermal analysis (DTA) (Figure 1). Magnetostriction measurements have been done by using resistance strain gauge which was placed along the preparation length of the ribbon. The variation of spontaneous magnetostriction of the specimens annealed at different temperatures is measured and compared with the magnetostriction value of the as prepared specimen using melt spinning techniques employed by Duwez and Willens [1], Pond and Maddin [2] and Asgar [3]. When annealing temperature was increased, the observed magnetostriction values for a particular field and also the saturation magnetostriction corresponding to the highest field needed, decreased. The results are explained in terms of strain induced anisotropy as pointed out by Predecki *et al* [4], Cohen [5], Hara [6], Luborsky *et al* [7] and Egami *et al* [8]. The specimen develops asymmetry with respect to the direction which is parallel to the length along which the ribbon is formed.

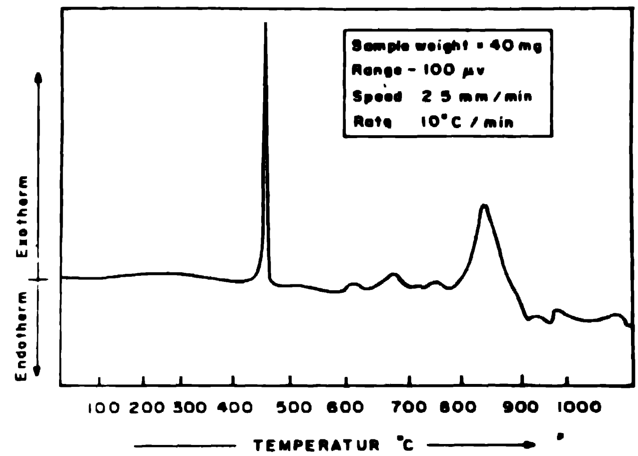

Figure 1. DTA Trace of amorphous iron-boron ribbon ($Fe_{82}B_{18}$)

Iron-boron ribbon with composition $Fe_{82}B_{18}$ has been prepared by melt-spinning technique [3] having thickness 55 μm and has been annealed at different temperatures starting from the ambient temperature to 300°C at intervals of 50°C. The effect of annealing on saturation magnetostriction and the field dependence of magnetostriction, have been studied using very thin electrical resistance strain gauges. Although there are some difficulties in using strain gauges for magnetostriction measurement in ribbons, which are specially thin and are thus constrained to having spontaneous deformation when strain gauge is bonded on it, there are advantages also in using this technique. For example, the magnitude of strain and its direction with respect to the direction of magnetization can be measured very accurately. This is done by bonding thin foil type strain gauge in the predetermined direction under a microscope and by measuring the variation of the strain with respect to the direction of the applied field, which for sufficiently high field is assumed to be coincident with the direction of magnetization. Out of the prepared ribbons, we choose the thickest for the present measurement to partly overcome the problem of the ribbon being constrained from free deformation due to the bonded strain gauge.

The amorphousity of the ribbon was checked by X-ray diffraction and the glass transition temperature was measured by DTA. The strain gauge was bonded parallel to the length of the ribbon, the direction along which the ribbon was prepared. The exact angular position of the strain measuring axis of the ribbon with respect to the direction of magnetization, was determined by varying the direction of the magnetic field with respect to the specimen. This is done by using the fact that when the magnetic field is along the easy direction of magnetization, one gets the maximum value of the saturation magnetostriction due to rotation of the magnetic field by 90°, shown in Figure 2. The angular position in this figure indicates arbitrary values. This shows a minimum magnetostriction at 133° and a maximum at 233°. The minimum position at 133° is identified as the 0°-position of the magnetic field with respect to the gauge direction, and the maximum at 233° is identified as the 90°-position of the field with respect to the gauge direction.

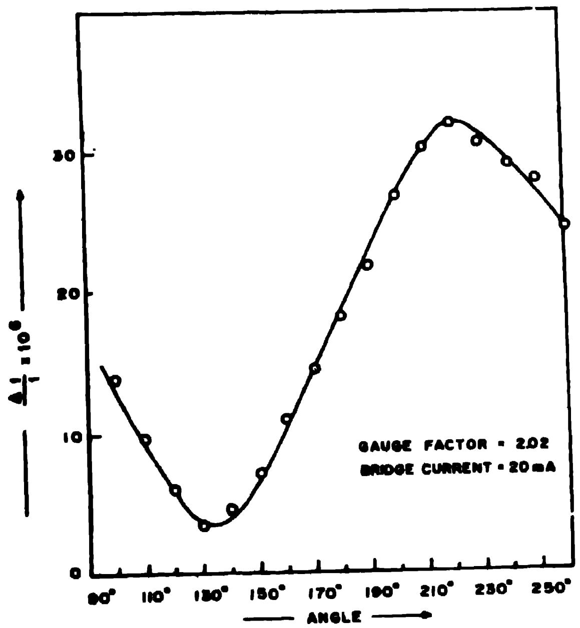

Figure 2. Magnetostriction *vs* angular position of the field.

Six specimens were cut from the main ribbon and were annealed at different temperatures for 2.5 hours. The annealing temperature was varied with 50°C intervals from room temperature to 300°C. Each specimen was subjected to increasing applied field and the differential magnetostriction was measured due to rotation of the magnetic field from parallel to the perpendicular position of the field with respect to the direction of the strain gauge. The variation of the minimum field needed for saturation magnetostriction is determined for each annealed specimen. The macroscopic magnetostriction representing the fractional change in length of a specimen is related to the macroscopic magnetoelastic constant which is considered as an average over the local elastic contributions. Magnetostriction is measured using the relation

$$\Delta R / R = G \Delta L / L,$$

where $\Delta R/R$ is the fractional change in resistance, G is the gauge factor and $\Delta L/L$ is the strain along the gauge direction. This technique is developed by Goldman [9], Lee and Asgar [10] and others.

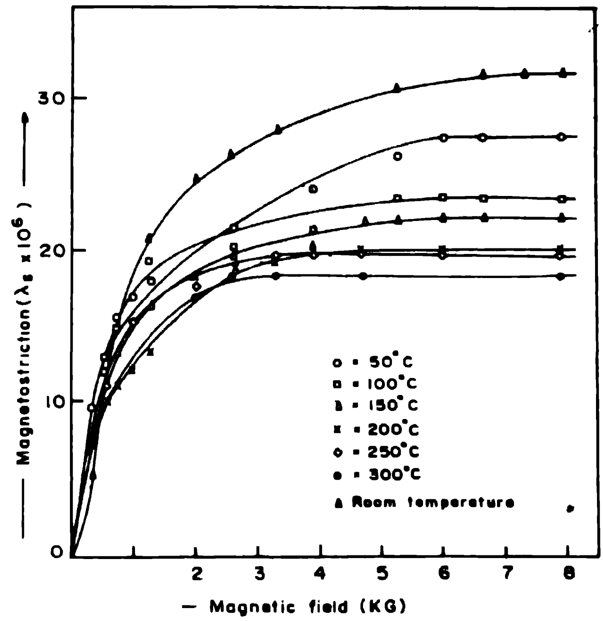

Figure 3. Magnetostriction *vs* magnetic field for different annealing temperature of $Fe_{82}B_{18}$ ribbon.

Assuming that the amorphous materials can be treated in the same way as polycrystals in respect of the distribution of the strain axes, the linear magnetostrictive strain can be written as

$$\lambda = \frac{3}{2}\lambda_s\left(\cos^2\theta - \frac{1}{3}\right),$$

where θ is the angle between the direction of the applied field and hence magnetization, and λ_s represents the saturation magnetostriction constant. By rotating the magnet from perpendicular to parallel position with respect to the strain measuring direction, we find

$$\lambda_S = \frac{2}{3}(\lambda_\pi - \lambda_\perp).$$

These are shown in Figure 3. The other aspects which are determined from these measurements are the variation of saturation magnetostriction and the relative motion of the

180° and 90° domain walls as affected by annealing. Figure 4 shows how the saturation magnetostriction decreases with the annealing temperature. Figure 5 is constructed from the magnetization *versus* field curve measured by Vibrating Sample Magnetometer (VSM), and the magnetostriction *versus* field curve measured by strain gauge technique. The extreme point along the X-axis of Figure 5 represents saturation magnetization and that along the Y-axis represents the saturation magnetostriction for each graph corresponding to a particular annealing temperature.

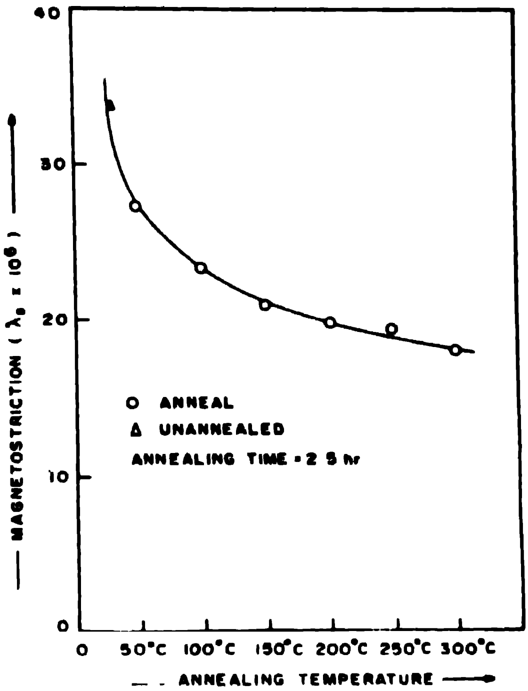

Figure 4. Magnetostriction *vs* annealing temperature of $Fe_{82}B_{18}$ ribbon.

Although amorphous ribbons are expected to be macroscopically isotropic, there is anisotropy in the microscopic scale as shown by Vazquez *et al* [11], Gonzalez and Kulakowski [12] and Hernando *et al* [13]. Furthermore, the ribbons developed some magnetic anisotropy due to the preparation process involved. As a result, some of the conventional theories of magnetization, magnetic anisotropy and magnetostriction can be applied to amorphous ribbons with certain limitations according to Gubanov [14] and Petrakovski [15].

Spontaneous magnetostriction in amorphous alloys originates from magneto-elastic interactions associated with local magnetic anisotropy and local strain which control the direction of magnetization. Origin of local strain has been discussed by Cochrane *et al* [16], Fahnle and Egami [17] and Suzaki and Ohta [18]. We assume that basically, the origin of magnetostriction in our amorphous ribbon is due to the dependence of the dipolar energy on interatomic distance according to Callen and Callen [19] and Lee and Asgar [20]. Thus, the strain induced in the ribbon during the preparation process produces spontaneous magnetostriction due to magneto-elastic effect. The magnitude of spontaneous magnetostriction is thus controlled by the amount of strain developed in the specimen during the preparation process. The strain induced is dependent on the speed at which ribbons are produced. The amount of strain is controlled by a competition between the reduction in the magnetic anisotropy due to magnetostrictive strain and the increase in elastic energy associated with this strain. For each composition, the thickness is determined by the flow rate of the flux. The tension and the stress on the specimen which are determined by speed and curvature of the wheel, contribute to the spontaneous magnetostriction.

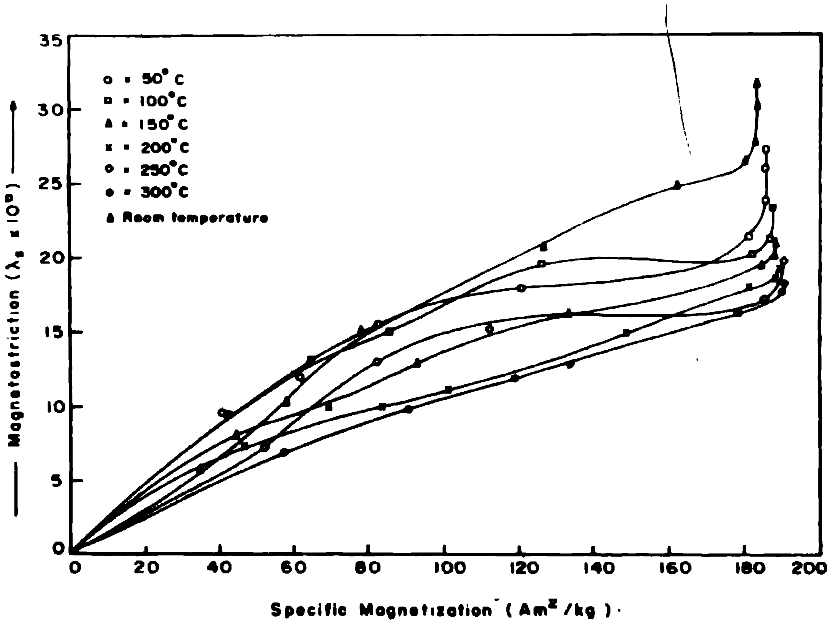

Figure 5. Magnetostriction *vs* specific magnetization for different annealing temperature of $Fe_{82}B_{18}$ ribbon.

Depending on the cooling rate and the complex stress developed in the ribbons, the magnetic domains develop their volumes, shapes and orientations. The sign of the magnetostriction determines the axis of easy magnetization of a specimen. For our specimen, the magnetostriction is observed to be positive which makes the direction of easy magnetization coincide with the direction of preparation length of the ribbon, because stress is developed along this length by the centrifugal force during the preparation of the specimen. The effect of annealing, as we have measured, is to reduce the saturation magnetostriction through reduction of stress. This explains the reduction in the value of the minimum field needed for attaining saturation magnetization [21] as also the saturation magnetostriction with increasing annealing temperature shown in Figure 3.

Figure 5 indicates the magnetostriction *versus* magnetization for different annealed specimens. These are obtained from field-dependence of magnetization and magnetostriction. From Figure 5, we obtain information regarding the relative movements of the 180° and 90° domain walls associated with magnetization process and as affected by annealing. This is because 180° domain wall movements do not give rise to magnetostriction, as the strain axis remains unaltered during this process.

For all the specimens it is observed that initial magnetization is mostly due to 180° domain wall motion and partly due to 90° domain wall rotation. Most of the magnetostriction arises at higher fields corresponding to saturation magnetization, involving mostly the 90° domain wall rotations.

Annealing removes the pinning centres of 180° domain walls more easily than those of the 90° domain walls. This is manifested in Figure 5 and in Table 1, where we find that last 2% of saturation magnetization corresponds to 19.6% of saturation magnetostriction for the unannealed ribbon, while the corresponding magnetostriction becomes 3.8%, when the specimen is annealed at 300°C.

Table 1. Saturation magnetostriction corresponding to last 2% of saturation magnetization.

Annealing temperature	At room temperature	50°C	100°C	150°C	200°C	250°C	300°C
Magnetostriction	19.6%	14 5%	8 2%	4.3%	6%	4.9%	3.8%

The value of the saturation magnetostriction as also the minimum field required for attaining saturation magnetostriction decrease with increasing annealing temperature. This is explained as due to reduction of the pinning centres to which the domain walls get stuck. It is also observed that the magnetization process becomes easier with increased annealing temperature. There is a lowering of the critical field needed for magnetic saturation with slight increase in the value of the saturation magnetization as reported by Sikder *et al* [21]. The present explanation of the dependence of magnetostriction on annealing temperature is also applicable to magnetization results for their dependence on annealing.

Although the magnetic characteristics of amorphous materials are discussed in general, on the assumption that the amorphous state of magnetic alloy of a given composition is independent of the technique used in preparing the specimen, in reality the secondary effects like domain orientation and strain induced magnetostriction of amorphous ribbons depend very much on the preparation process. The study of the effects of annealing on such specimen is, therefore, very important for controlling magnetic properties of amorphous magnetic materials.

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